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321 BULLFINCH ROAD
PANAMA CITY, FLORIDA 32407-7015

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USE OF EMERGENCY EVACUATION HYPERBARIC
STRETCHER (EEHS) IN SUBMARINE ESCAPE AND RESCUE

GARY W. LATSON, LCDR, MC, USNR
EDWARD T. FLYNN, JR., M.D.

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Submitted:


G. W. LATSON
LCDR, MC, USNR
Principal Investigator


E. T. FLYNN, M.D.
Co-Investigator

Reviewed:


D. G. SOUTHERLAND
CDR, MC, USN
Head, Biomedical Research Department


M. E. KNAFE, MC
CAPT, MC, USN
Medical Director


J. R. CLARKE
Scientific Director

Approved:


E. N. CHRISTENSEN
CDR, USN
Commanding Officer

Distribution: As Applicable
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INTRODUCTION

The United States Navy is currently evaluating small, lightweight hyperbaric chambers made of flexible reinforced fabrics for emergency recompression and transport of patients suffering from Decompression Sickness (DCS)^{1, 2}. One of the proposed areas of use is for treatment or transport-under-pressure of rescues from a disabled submarine (DISSUB) which has been internally pressurized. This report will review the capabilities of the Emergency Evacuation Hyperbaric Stretcher (EEHS), discuss its proposed uses, including indications and contraindications, and suggest protocols for implementation.

In the Submarine Rescue Mission, these one-man chambers could serve several functions. Most importantly, they could be rapidly deployed to any vessel of opportunity in the event that persons escaped from the DISSUB via the escape trunk prior to the arrival of major assets. Many of the survivors would likely suffer DCS, Arterial Gas Embolism (AGE), or some other form of barotrauma³. These simple, compact systems could be rapidly airlifted in limited quantities far sooner than a larger recompression system could be transported to the scene. Survivors with severe neurologic involvement might be salvaged by early recompression, or survivors with complicating injuries could be evacuated under pressure.

In the event of rescue using the Deep Submergence Rescue Vehicle (DSRV) with transfer of rescues to a Mother Submarine (MOSUB), a limited number of EEHS units could be used in the MOSUB to treat the most severe cases of DCS⁴. They could augment the capability of larger multi-place recompression facilities by allowing separation of patients with complicating injuries. Once isolated in the EEHS, the patient could be transferred to another facility for treatment, or could be treated on-site on a schedule best suited for his particular needs. Treatment of the remainder of the rescues would be more efficient without the need to alter decompression for the patient with complicating injuries.

Other uses of the EEHS besides the Submarine Rescue Mission will likely be developed in the future. These may include Special Warfare or Explosive Ordnance operations in remote locations, treatment of downed pilots suffering from altitude DCS⁵, and use in MEDEVAC operations. This report will not address these scenarios, but much of the information will be applicable.

COMPARISON OF AVAILABLE SYSTEMS

At the time this project was initiated, two systems were commercially available, both from foreign manufacturers. A Foreign Comparative Test program was initiated by NAVSEA 00C to compare the Hyperlite made by SOS Limited of the United Kingdom and the GSE Flexible Hyperbaric made by GSE Trieste Ltd. of Italy^{1, 2}. Comprehensive results of this evaluation will be available in a separate report⁶. Pertinent information will be reviewed as follows.

The requirements outlined in the EEHS test plan included the ability to transport the patient under pressure in fixed wing or rotary aircraft, and the ability to complete a U.S. Navy Treatment Table 6 during transport^{1,2}. This implies pressurization to at least 60 fsw (18.3 msw) (2.8 ATA) with delivery of 100% oxygen to the patient. Minimal weight was also a priority, with an aim of having a system that could be carried by as few as two to four people. Other considerations included ease of set-up, safety features, ability to use standard SCUBA cylinder gas supply for pressurization, a supply lock, communication system, and the potential for the addition of extra penetrators for intravenous therapy and medical monitoring.

Both of the systems under consideration meet most of these objectives, but there are significant conceptual and design differences between the two systems. Most importantly, the British Hyperlite seems to have been designed from the outset with the mission of evacuation in mind, while the Italian GSE Flexible Hyperbaric seems to have been conceived as an actual treatment chamber to be used in a remote location. The GSE advertises the capability of pressurization to 6 ATA (165 fsw) (50.3 msw), and has an option which allows the attachment of a second compartment which would allow an attendant to be in the chamber with the patient. While these capabilities offer a significant advantage in some circumstances, they add weight and complexity, which are disadvantageous for efficient evacuation.

Other features of note are summarized in Appendix A. For the remainder of this report, it will be assumed that the Hyperlite EEHS system will be the system used.

OPERATIONAL LOGISTICS

There are two situations where DCS or AGE could occur: (1) submariners exiting the DISSUB via the escape trunk and making a buoyant ascent through the water, and (2) submariners remaining in an internally pressurized DISSUB and being rescued by a rescue vehicle such as the DSRV, Submarine Rescue Chamber (SRC), or Submarine Rescue Diving and Recompression System (SRDRS).

In the escape situation, barotrauma from rapid pressurization in the escape trunk at depth followed by rapid decompression in the water column on ascent is likely. This would include ruptured tympanic membranes, inner ear and vestibular damage, pulmonary overinflation syndrome with pneumothorax, and AGE. DCS could occur if the DISSUB was internally pressurized prior to escape, or if the time spent under pressure in the escape trunk was sufficient to absorb the critical amount of nitrogen necessary for inducing DCS³.

In the event of rescue using a pressurized transfer vehicle such as the DSRV, acute barotrauma would be less likely because gradual decompression would occur in the rescue vehicle. Serious DCS could occur as a result of decompression from saturation, particularly if the internal pressure of the DISSUB is greater than 2 ATA and decompression is rapid.

Other injuries, most notably thermal burns, carbon monoxide poisoning, smoke inhalation, acute head injuries, and musculoskeletal trauma will likely be encountered. In some circumstances, these injuries may be benefited by hyperbaric oxygen therapy on treatment schedules different from those used to decompress uninjured members of the crew.

In any of these situations, it is likely that many of the rescuees will need recompression therapy. The options available for such treatment on the scene are likely to be very limited. Ships equipped with multi-place hyperbaric chambers suitable for these treatments are not likely to arrive on the scene in less than 24 to 48 hours, and would probably not be able to handle all of the casualties involved. American submarines that would be employed as the recipient of rescuees from the DSRV (designated "MOSUBs") cannot be internally pressurized due to the sensitivity of certain components and thus cannot effect a gradual decompression. In most areas of the world, the number of rescuees that may need to be treated would quickly overwhelm local shore facilities.

When considering these factors, it becomes apparent that recompression chambers which could be rapidly transported to a remote site, deployed on a variety of vessels without complicated support systems, and transported with the patient under pressure if necessary, would be a valuable asset. The Hyperlite, or similar EEHS system, may be able to meet these needs:

- They are easily stored. Deflated, they are packed in trunks (approximately 2 ft³); the complete system, including trunks, weighs approximately 265 lb (120 kg).
- They could be easily transported by truck, van, fixed wing aircraft or helicopter. They could be transported at sea by a variety of small, fast craft or dropped by cargo parachute if needed, and would thus probably be the first recompression asset on-site.
- They could be transferred to any surface ship or into a MOSUB.
- They require only a standard SCUBA cylinder for pressurization and a medical oxygen cylinder for administration of oxygen. They do not require electricity or additional support systems.
- They can be used in a small space, requiring as little as 8 ft x 3 ft of deck space per unit.
- They can be taken into, or out of, most standard recompression chambers while maintaining pressure. This allows the transfer of patients into, or between, other chambers.

- They can be transported by boat, truck, and fixed wing or rotary aircraft, with a patient inside under pressure. This allows evacuation under pressure if necessary.
- They are relatively simple and intuitive to operate, minimizing training requirements.
- They are capable of pressurization to 2.8 ATA, the depth used in U.S. Navy Treatment Table 6 for treatment of DCS and AGE, and are capable of delivering 100% oxygen to the patient at depth. This treatment capability matches the recommended treatment for most cases of DCS and AGE.

Strategies for deploying the EEHS are recommended as follows:

1. A supply of EEHS units (number to be determined-see discussion later in this report) would be kept in storage along with other Submarine Rescue Mission assets at facilities with rapid access (potential sites include Deep Submergence Unit (DSU) - San Diego, CA; Navy Experimental Diving Unit (NEDU) - Panama City, FL; Norfolk, VA or New London, CT).
2. If other EEHS units become assigned to military diving units, such as Mobile Diving and Salvage Units (MDSUs), Explosive Ordnance Disposal (EOD) units, or Special Warfare units, a registry of these units would be maintained by the submarine rescue coordinator. These EEHS systems, along with trained operators, could be called upon when needed.
3. Upon notification of need, the EEHS units would be airlifted to the most efficient transfer site to be transported to the DISSUB scene. A limited number of units could be dropped by cargo parachute if needed urgently. Personnel trained in the use of the EEHS would be activated and would accompany the units to the scene.
4. If submarine personnel have evacuated the DISSUB through the water using the escape trunk, the EEHS units would be assembled and used immediately to treat the most seriously affected by DCS or AGE on the first vessel of opportunity. A triage system (see Appendix B) would be used in the prioritization of subjects to receive recompression. If evacuation assets are available, those subjects with complex injuries needing medical treatment in addition to recompression would be evacuated using an EEHS if DCS or AGE was also present with a severity justifying transfer under pressure.
5. If submarine personnel are to be rescued using the DSRV or other pressurized rescue vehicle, the EEHS systems available would be prepared on the first available surface ship in anticipation of need when the rescuees are delivered, after completion of as much decompression as possible in the rescue vehicle. If time and operational factors permit, a limited number of EEHS systems (perhaps

up to ten) could be transferred to the MOSUB before the first batch of rescues are delivered by the DSRV. The EEHS could be used to recompress the most severe cases of DCS or AGE while the MOSUB prepares for transfer to a surface ship or transit to port. It is notable that the Hyperlite EEHS has been taken aboard a U.S. Navy MOSUB and multiple sites large enough to operate it were identified⁷. It was necessary to unpack the Hyperlite from its shipping containers in order to fit the components through the hatches, and it was difficult, but possible, to pass the flexible hull through the hatch with the ladder in place (removal of the ladder would be recommended in the future). Other components were easily loaded. Moving the flexible hull within the submarine was also difficult, requiring at least two people, but could be accomplished. The following spaces were found to be adequate for operation of the Hyperlite:

- Combat systems Engineering Space
- Yeoman's space
- Forward Berthing
- Middle Level Head
- Aft Berthing
- Crew's Mess
- Wardroom
- Torpedo Room

All aft spaces on the MOSUB were excluded from consideration. Forward, the Hyperlite could be accommodated in 21 places outside of the torpedo room. The torpedo room could accommodate 16 to 20 Hyperlite systems, the amount depending upon the number of torpedos on board and the amount of other supplies stored in the area. It is recognized that many of the spaces would present logistical difficulty for actual use, but they do offer the required dimensions and present options for consideration.

Possible sources of compressed air and oxygen to support the use of EEHS systems were also identified. There are significant technical and safety issues to be resolved, but it seems that there is at least the possibility of using the oxygen and air banks to refill portable cylinders for use with the EEHS.

It is unlikely that an EEHS could be used to transfer a patient off of submarine, due to the complexity of fitting the occupied EEHS through the vertical portion of the hatch.

6. If fully equipped assets arrive on the scene, and enough multi-place recompression chambers are available to treat the number of rescues involved, the EEHS would be used in an adjunctive role. Patients requiring advanced medical care for complex injuries could be removed from a larger chamber, while maintaining pressure, for evacuation to a medical facility or treatment on-site on a different decompression schedule. In this way, decompression of the larger cohort would not be slowed or otherwise compromised.

ESTIMATES OF NUMBER OF EEHS UNITS REQUIRED

The number of EEHS units to be made available is open to debate. If funding was unlimited, one EEHS per submarine crewmember would be optimal, but this is not likely to be feasible. If past experience is to be used for guidance, the sinking of the Peruvian submarine Pacocha in 1988 should be considered⁸. After a collision on the surface, the submarine sank in 140 fsw (42.7 msw). Out of 49 crewmembers, 23 abandoned ship on the surface, and 26 went down with the submarine. Of the 26, 22 lived to escape via the escape trunk after approximately 23 hours at an estimated DISSUB internal pressure of 54 fsw (16.5 msw). Twenty out of these 22 suffered DCS or AGE requiring recompression therapy, which was accomplished with a variety of shore based and at-sea assets with variable delays. One escapee died, one suffered severe brain injury, and several have residual neurologic injury from DCS. Immediate recompression with a system such as the EEHS might have greatly reduced permanent injury.

Consider that modern American attack submarines carry a crew of over 100 people, and a ballistic missile submarine may have over 200 people aboard at times. It is likely that most of the crew would be trapped in the submarine, and it is possible that the internal pressure would rise to at least 50 fsw (15.2 msw). If they were to exit via the escape trunk after saturation at this depth, it is estimated that over 80% could suffer AGE or DCS. Approximately 25 EEHS systems, rapidly deployed, would be expected to save several lives and reduce neurologic injury in many more. For more detail on the derivation of these estimates, see Appendix F.

Alternately, if the crew remained on board awaiting rescue, they could be decompressed at least partially in the DSRV or other rescue vehicle. In all likelihood, due to the need for rapid turnaround to rescue remaining crew-members, the decompression time would be less than optimal, (assume four hours) and an incidence of DCS of over 60%, might result⁹. In this scenario, if multi-place chambers were not yet available, about 13 EEHS units would be expected to be utilized.

If the full complement of the future SRDRS system, with multi-place recompression assets capable of treating the entire crew becomes available, the EEHS will be needed primarily to care for those with complex injuries needing customized care or evacuation. In this case, ten units would probably be sufficient.

The cost of this number of EEHS units may be justifiable when compared to the cost of medical care for the neurologic injuries that might be prevented. Additionally, the cost of compensation for these injuries and/or deaths, which might be prevented by expedient recompression treatment using the EEHS, should be considered.

MEDICAL INDICATIONS FOR USE OF EEHS

As mentioned above, several conditions needing recompression therapy are likely to be encountered in a Submarine Rescue Mission. They are detailed as follows:

DECOMPRESSION SICKNESS (DCS)

DCS is the condition which occurs when the body absorbs an inert gas (the nitrogen component of air) at an increased pressure and subsequently is brought to a lower pressure too rapidly to allow the dissolved gas to be eliminated from the body without the formation of bubbles in the bloodstream or tissues¹⁰. This can occur in submarine crewmembers in several ways. If the internal pressure of the DISSUB rises due to partial flooding of compartments or the use of emergency breathing gases, the crewmembers will be exposed to an increased ambient pressure. This would be analogous to a diver at depth, a caisson worker, or an occupant of a hyperbaric chamber. If the crewmembers live at this increased pressure for several hours, or even days, before being rescued, their bodies will have absorbed a significant amount of inert gas (nitrogen). If they are brought back to surface pressure rapidly, nitrogen bubbles may form in their tissues. These bubbles may cause a wide variety of pathologic events, referred to as Decompression Sickness (DCS).

DCS can also occur without the submarine being internally pressurized if crewmembers escape using the escape trunk³. In order to escape, the escape trunk must be rapidly flooded and pressurized to the pressure (depth) outside the submarine. The crewmember will be exposed to this increased pressure for the time it takes to complete the escape procedure, exit the submarine, and swim to the surface. During this time, he will absorb nitrogen into his tissues, and this absorbed nitrogen may be sufficient to cause DCS upon return to surface pressure.

DCS is commonly discussed as two types; Type I DCS involves pain (usually in the joints) as the only symptom, whereas Type II DCS is more serious and involves neurologic, circulatory, or respiratory symptoms. In the submarine rescue scenario, the focus will be upon Type II DCS because it can lead to life threatening complications and permanent neurologic injury. Type II DCS may occur immediately upon surfacing or up to 24 hours later, and may cause neurologic symptoms ranging from mild numbness to severe paralysis, visual impairment, coma, or death.

The treatment of choice for Type II DCS is recompression and hyperbaric oxygen therapy. With prompt recompression, resolution of DCS occurs in over 90% of cases¹¹. Delay in treatment reduces the chance of resolution. For this reason, early treatment using the EEHS system should yield improved results. In a submarine rescue situation, it is likely that there will be more patients with DCS than available recompression chamber spaces, and thus decisions will have to be made concerning which patients to recompress first. Severe neurologic or cardiovascular involvement will be a high priority, whereas less severe cases may be allowed to await therapy. A triage/prioritization algorithm is proposed (see Appendix B) to aid in this decision making process.

Treatment will be based on the U.S. Navy Treatment Table 6, which has been the standard treatment for Type II DCS in the U.S. Navy for several decades. This protocol

involves recompression to 60 fsw (18.3 msw) (2.8 ATA) pressure and breathing 100% oxygen. Variations from the standard regimen may be allowed at the discretion of the on-site Undersea Medical Officer. The protocol is detailed in Appendix C.

ARTERIAL GAS EMBOLISM (AGE)

AGE is the condition which occurs when ascent or reduction in pressure occurs so rapidly that air trapped in the lungs expands and ruptures the air sacs in the lung. Bubbles of gas (gas emboli) enter the circulation, pass through the heart, and are transmitted via the arterial circulation throughout the body, where they can occlude the circulation to vital tissues causing damage similar to a stroke or heart attack. This could occur in the DISSUB scenario as crewmembers rise rapidly to the surface after exiting through the escape trunk. It is unlikely to occur if crewmembers are rescued using the DSRV or other pressurized rescue vehicle, because the decompression will be relatively gradual in a controlled environment.

Treatment for AGE follows the same basic principles of recompression and hyperbaric oxygen therapy as treatment for DCS, and may be accomplished using the EEHS. Some experts advocate a more aggressive application of pressure, up to 165 fsw (50.3 msw) (6 ATA). The need for this degree of recompression however is controversial. The EEHS, as currently envisioned, will only allow recompression to 2.8 ATA with 100% oxygen, which many experts consider to be sufficient for AGE¹². A proposed treatment protocol is detailed in Appendix B. AGE is more likely to present with severe neurologic symptoms, unconsciousness, and cardiovascular instability, and will thus be a high priority for recompression.

THERMAL BURNS, CARBON MONOXIDE POISONING, AND SMOKE INHALATION

In a submarine collision, attack, or malfunction, fire is a significant possibility, and due to the crowded conditions, severe burns are likely. Hyperbaric oxygen therapy has been shown to be a helpful adjunctive therapy for burns¹³. There is evidence that it reduces tissue edema in the acute phase¹⁴. Thus, patients with significant thermal burns would be candidates for therapy in the EEHS, with or without co-existent DCS. Use of the EEHS would allow these patients to be separated from the remaining cohort and evacuated as soon as possible. (See Appendixes D and E.)

Carbon monoxide (CO) poisoning often coexists with burns, and would be highly likely in the confined atmosphere of a DISSUB. Hyperbaric oxygen therapy has gained recognition as a valuable, and perhaps life-saving, treatment for CO poisoning, and could be accomplished in the EEHS¹⁵. (See Appendix D.)

Smoke inhalation including inhalation of toxic products such as cyanide, phosgene, and chlorine gases is another possibility. Hyperbaric oxygen has also been proposed for therapy of smoke inhalation and cyanide poisoning but may be relatively contraindicated in chlorine gas exposure due to pulmonary injury¹⁶.

TRAUMA AND CRUSH INJURY

Traumatic injuries would be expected in most situations where a submarine becomes disabled. Crushed extremities with ischemic tissue and developing compartment syndromes may benefit from hyperbaric oxygen therapy, which could be provided in an EEHS. (See Appendix D.)

It becomes evident that the possible uses for the EEHS are numerous, and decisions regarding which patients will receive priority in treatment may be complex. As an aid in this process, we propose a triage algorithm based on the severity of DCS/AGE, co-existent medical problems, contraindications, and resources available. (See Appendix B.)

CONTRAINDICATIONS FOR USE OF THE EEHS

While the EEHS system is a valuable tool, it has significant limitations, and may pose serious hazards if used inappropriately. It is basically a monoplace hyperbaric oxygen treatment chamber, similar in design and capability to the chambers (such as those made by Sechrist) used in hundreds of hospitals and medical facilities throughout the world for thousands of treatments annually. We can draw from the extensive experience in this field for both capabilities and cautions.

The most serious limitation of any monoplace hyperbaric system is the loss of "hands on" access to the patient. While this presents many challenges to physicians not accustomed to this situation, physicians experienced in the use of monoplace chambers have learned that many of the problems can be overcome with careful preparation and vigilance. Recommendations for care of critically injured patients in the EEHS are addressed in Appendix E.

The most important concern for use of the EEHS should be consideration of airway management. If the patient is not fully conscious and capable of maintaining his own airway, he should not be placed in the EEHS unless personnel skilled at airway management are continuously managing the patient. The risk of airway obstruction in an unconscious patient is always present, and the EEHS offers only very limited ability to observe ventilation. Anoxia from airway obstruction is worse than most cases of DCS or AGE, and the relative risks must be carefully weighed. The use of airway adjuncts, such as oral or nasopharyngeal airways, endotracheal intubation, laryngeal mask airway, esophageal obturator airway, or other devices may be helpful, but should only be used by skilled personnel. Their use is further addressed in Appendix E.

Acute head injury, by itself, is not necessarily a contraindication, but if the patient were unconscious, the above discussion would apply. Vigilance would be necessary to follow changes in level of consciousness. Trauma to the face, particularly involving the airway, requires careful consideration.

Chest trauma or the presence of pneumothorax or pneumomediastinum should be considered a relative contraindication due to the possibility of tension pneumothorax. Unlike in a multi-place hyperbaric chamber, a pneumothorax could not be vented at depth, and would thus be worsened on decompression with the possibility of development of tension pneumothorax. Immediate thoracostomy upon exit from the chamber could be performed, but this would be a very hazardous procedure. If the need for recompression was extreme and the EEHS was the only available asset, tube thoracostomy prior to recompression would be an option.

Significant multi-system trauma with shock would require careful consideration before use of the EEHS. Interventions necessary for support of shock, including large volumes of fluids, vasopressors, respiratory support or CPR would be compromised by recompression in an EEHS. Some proposed modifications and accessories for the EEHS, including intravenous access system, enhanced monitoring, and a ventilator, could become available (see Appendix E), which could provide the ability to treat some patients in shock, but these capabilities are not currently available. The complexity of providing these capabilities is such that it is not likely to be viable in a mass casualty situation.

Extremity trauma may present logistic difficulties due to patient positioning and the process of loading the patient into the EEHS. The management of the injury may be complicated, but this should not be a contraindication. In fact, as mentioned earlier, hyperbaric oxygen may be beneficial in many cases of extremity trauma.

HAZARDS

Fire hazard is a major concern in any hyperbaric chamber, and appropriate precautions must be conscientiously followed in the use of the EEHS due to the use of oxygen and lack of any fire suppression system. With proper use of the built in breathing system (BIBS), oxygen levels within the EEHS will remain under 25%, but leakage from a poorly fitting BIBS can raise the oxygen level within the EEHS to over 30%, which could increase the risk of fire⁶. Careful attention to proper use of the EEHS is mandatory, and monitoring of the oxygen level is desirable. Strict adherence to standard fire safety precautions, including elimination of flammable materials from the chamber and use of 100% cotton materials is strongly advised. Clothing soiled with oil or grease should be removed and replaced with clean cotton garments. Any fire would likely be catastrophic not only to the chamber occupant, but to bystanders as well.

There are hazards associated with use of pressurized systems. The high-pressure air and oxygen sources, valves, hoses, and regulators are similar to those commonly used for SCUBA systems and medical oxygen supplementation systems. The chamber itself is pressurized to a maximum of 30 psig, equivalent to the pressurization of an automobile tire. The Hyperlite has been shown in destructive testing to have a failure pressure of approximately 200 psig, and failure resulted in rapid leakage rather than catastrophic bursting¹⁷.

Excessive environmental heat could compromise use of the EEHS in some situations. Testing at NEDU indicates that the internal temperature of the EEHS may range from 2°-15° F (1° C - 8° C) higher than the surrounding environment⁶. Internal chamber temperatures over 85° F (29.45° C) for extended periods could lead to potentially dangerous heat stress in patients¹⁸. Means of reducing the temperature inside the chamber include venting and cooling the exterior of the chamber with cool air, water, or ice. Monitoring of internal temperature is advisable if possible.

Personal hygiene, particularly management of urine and feces, must be attended to. This is particularly important due to the small volume of breathable atmosphere within the chamber, making atmospheric contamination with ammonia or hydrocarbons a concern, although it is mitigated somewhat by the fact that the patient should be breathing from the BIBS rather than chamber atmosphere. Patients capable of caring for themselves should be provided urinals, condom catheters, or bedpans. Condom catheters or foley catheters should be used for debilitated patients. Absorbent diapers are an option, but would not be optimal.

POLICY CHANGES

Current U.S. Navy policies do not cover the use of the EEHS. Guidelines for recompression therapy for diving injuries outlined in the U.S. Navy Diving Manual are directed at the use of multi-place hyperbaric chambers, and are primarily concerned with diving related injuries. Since the use of the EEHS in the Submarine Rescue Mission would be emergency medical management, and would be unrelated to diving per se, it could be addressed in a manner similar to the use of other emergency medical devices, such as oxygen delivery systems, MAST suits, ACLS adjuncts, etc.

If an EEHS system is later evaluated and approved for other diving related purposes, which is quite possible, appropriate changes to the U.S. Navy Diving Manual, or other appropriate instruction, would be indicated covering those applications.

TREATMENT PROTOCOLS

Protocols for treatment of DCS/AGE at the scene using the EEHS will generally follow the schedules outlined in U.S. Navy Diving Manual¹⁰, Treatment Tables 5 and 6. It should be emphasized that if these schedules are followed with respect to depth and oxygen cycles, the patient should be able to be decompressed to the surface (ascent rate not to exceed 60 fpm) at any time during treatment for emergencies, other interventions, or interruption of treatment if necessary. It is conceivable that if there were a large number of severely affected casualties, treatment times could be shortened to accommodate more patients in shorter periods of time. While not optimal, this could be an acceptable practice, particularly if new patients develop symptoms more severe than those of patients already receiving treatment. While this should only be considered in extreme circumstances, and by experienced physicians, proposed guidelines should leave sufficient flexibility for the DMO on-site to adjust the schedules based on his assessment of priorities. (See Appendix C.)

Protocols for transfer under pressure and evacuation may vary slightly from treatment protocols, but should generally follow the same principles. In most situations, U.S. Navy Treatment Table 6 will serve as the recommended schedule. Clear documentation of the treatment schedule will be vitally important if care of the patient is transferred during treatment. Ending a recompression treatment while in transit, particularly if in an aircraft, should be avoided. (See Appendix D.)

CONCLUSION

The EEHS represents a significant advance in acute management of DISSUB casualties, but many logistical issues will require careful consideration and planning. Procurement, staging, transport, and training of qualified personnel will be major issues that should be addressed as soon as decisions on the incorporation of the EEHS into the U.S. Navy Submarine Rescue Mission are made. With foresight, many lives could be saved and disabling permanent injuries could be prevented.

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APPENDIX A

DESCRIPTION OF SOS HYPERLITE EEHS SYSTEM

BASIC MATERIALS

- "Filament wound para-aramid fiber in flexible polymeric silicone matrix" (similar to "Kevlar"), with a cotton fabric cover

WEIGHT

- 165 lb (74.8 kg) complete (not including gas supply cylinders)

DIMENSIONS

- 88.5 inches (225 cm) long by 23.5 inches (60 cm) outer diameter

END PLATES

- Transparent acrylic plastic which seal against the lip of the tube by pressure from the inside (no mechanical latch)

OXYGEN ADMINISTRATION (BIBS) SYSTEM

- Includes a demand regulator supplying 100% oxygen to an oral-nasal mask with overboard dump of exhaled gas.
- Includes a switch valve on control panel to easily change BIBS gas from oxygen to air.
- Oxygen required for Standard U.S. Navy TT6 – 200 standard cubic feet (approximately equal to one "K" cylinder).
- A semi-closed circuit rebreather system has been proposed in concept by Navy personnel to conserve oxygen, but is not currently available.

GAS SUPPLY AND CONTROL SYSTEMS

- Hoses enter at the center of the end plates in a long axis orientation. They are not subject to damage if the unit rolls or must pass through a narrow opening during transport.

- Control module is intuitive and easy to understand. Controls for supply, exhaust, pressure, and BIBS gas have positive positions. Gauge readings are not altered by control settings.
- Air required for pressurization – 40 standard cubic feet (two 80 standard cubic feet cylinders recommended for a U.S. Navy TT6 to provide sufficient air for air breaks).



ILLUSTRATION A-1. SOS HYPERLITE EEHS SYSTEM

APPENDIX B

TRIAGE ALGORITHM FOR THE INITIAL MANAGEMENT OF DISSUB CASUALTIES

The possible uses for the EEHS for treatment of DISSUB casualties are numerous, and decisions regarding which patients will receive priority in treatment may be complex. As an aid in this process, we propose a triage algorithm based on the severity of DCS/AGE, co-existent medical problems, contraindications, and resources available.

There are many possible scenarios, depending on the method of escape or rescue from the DISSUB, the assets available, and the number and type of casualties. For the sake of discussion, two distinct situations will be discussed:

- 1) Submarine crewmembers exit the DISSUB via the escape trunk before any major assets have arrived on scene.
- 2) Submarine crewmembers are rescued from the DISSUB using the DSRV or other pressurized rescue vehicle. Major assets, such as surface ships with limited recompression facilities, as well as evacuation assets, are on-site.

Rescue by use of the Submarine Rescue Chamber (SRC) (McCann Bell) would fall between these two situations, as the rescuees would probably not suffer barotrauma, but would have a very short, almost surely inadequate, decompression and thus a high incidence of DCS. If a McCann Bell is on-site, it is likely that at least one standard multi-place decompression chamber would also be available.

These two scenarios represent the ends of the spectrum of possibilities; reality will almost certainly lie somewhere in between. The situations are sufficiently different to call for different decision algorithms; to attempt to address all possibilities into one algorithm would be overly complicated.

The major factors to consider in either situation include:

- The presence and severity of other injuries besides DCS/AGE. The treatment of life threatening trauma will obviously supercede recompression, particularly if recompression compromises access to the patient.
- The severity of DCS/AGE. Neurologic or cardiovascular involvement obviously is a higher priority than pain-only symptoms. Furthermore, paralysis of major muscle groups, or gross cerebral deficits are more significant than sensory findings (i.e., numbness or paresthesia). Rapidity of onset is a consideration; DCS presenting early and changing rapidly should probably be treated more aggressively than slowly evolving symptoms.

- The presence of contraindications to recompression therapy.
- The assets available. Are there enough recompression chamber spaces to accommodate all of the serious cases? Is evacuation to another facility possible within a reasonable time?
- Complicating conditions. Does the patient have problems that, although not contraindications, would make recompression in an EEHS difficult?
- Likelihood of success. This is frequently the most difficult issue. Should a recompression asset be tied up with a case unlikely to recover while other less severely injured patients may have a better chance of recovery?

APPENDIX B1

TRIAGE ALGORITHM FOR ESCAPE

Crewmembers escape via escape trunk and make ascent through the water column. AGE is a significant risk. DCS is a possibility, particularly if crew-members have stayed on internally pressurized DISSUB for over four hours. Hypothermia, drowning, and an acute barotrauma of ears, sinus, or lungs are also likely. Rescue assets are likely to be very limited if escape occurs a short time after mishap. Other injuries could be encountered, but it is unlikely that severely injured members could make a swimming escape.

It is possible that EEHS units may be the only recompression assets available, and there may not be enough to treat all patients.

STEP ONE

Assess for life threatening injuries other than DCS/AGE, particularly hypothermia and near drowning. If present, address injury. If use of EEHS would compromise care of other conditions, defer recompression until immediate threat stabilized. Supplemental oxygen, if available, is strongly recommended.

- ♦ If no other immediately life threatening injuries present, go to step two.

STEP TWO

Assess for DCS/AGE. This should be a rapid screening exam:

- ♦ Does the subject complain of any weakness, paralysis, visual disturbance, unsteadiness or cognitive defect?
- ♦ Can the subject answer simple questions, recognize a visual object, stand, walk, reach above his head with both arms, and grip?
- ♦ If gross deficit found, go to step three.
- ♦ If no gross deficit, observe expectantly, treat other injuries when feasible, and provide fluids and surface oxygen if available. Re-assess periodically, and in more detail, when recompression chamber space available.

STEP THREE

Rule out possible contraindications to recompression in the EEHS:

- ♦ Unconsciousness (unless skilled personnel available)
- ♦ Any airway compromise
- ♦ Chest trauma
- ♦ Pneumothorax (particular attention to this should be paid if patient has rapidly developing neurologic symptoms which could be AGE).
- ♦ Shock
- ♦ Head injury
- ♦ If contraindications exist, defer recompression until problems addressed (i.e., chest tube placed for pneumothorax, shock stabilized, or airway secured by skilled personnel).
- ♦ If no contraindications, go to step four.

STEP FOUR

- ♦ Assess the likelihood of recovery compared to other candidates for recompression therapy if resources are limited. Avoid dedicating scarce resources for an indeterminate time period if patient is unlikely to recover.
- ♦ Also consider co-existent conditions other than DCS/AGE which would benefit from hyperbaric oxygen therapy, such as carbon monoxide poisoning or burns. While these conditions will probably not be the primary concern for decisions regarding allocation of EEHS, they may be a factor.

STEP FIVE

- ♦ Special considerations requiring preparation. If patient needs extensive preparation (i.e., chest tube, wound care, etc), it may be more efficient to treat another patient in the EEHS while this patient is being readied.

STEP SIX

- ♦ At earliest opportunity, place patient in EEHS, using criteria discussed above to prioritize which patients will be treated first. Teach use of BIBS and equalization techniques, and compress (patients unable to equalize the pressure in the middle ear space may require decongestants, slow compression or

myringotomy). Give 100% oxygen via BIBS system. Assess for response to treatment. (See Appendixes C, D, or E for specific treatment profiles.)

- ✦ All patients should be evaluated continuously. If a patient not under recompression deteriorates to the point that his symptoms exceed those of patients in a EEHS, consider decompressing the least serious EEHS patient in order to recompress more seriously injured patients. Weigh this decision very carefully.
- ✦ If evacuation is a possibility, consider transport under pressure using EEHS. (See Appendix B3.)

APPENDIX B2

TRIAGE ALGORITHM FOR RESCUE

Submarine crewmembers remain in DISSUB until a pressurized rescue vehicle (DSRV, SRDRS, or comparable system) arrives. Other assets are likely to be on scene or arriving shortly. Decompression is likely to have been attempted in rescue system, but may have been inadequate. There is likely to be a latency period between surfacing and onset of DCS ranging from one to four hours. Acute barotrauma is unlikely. Other injuries, some severe, are possible because of the capability of DSRV/SRDRS to transport more severely injured persons.

STEP ONE

- ♦ Assess for life-threatening injuries other than DCS/AGE, particularly hypothermia, burns, toxic gas inhalation, major head, chest or abdominal trauma, or hemorrhage. If present, address injury. If use of EEHS would compromise care of other conditions, defer recompression until immediate threat stabilized.
- ♦ If no other immediately life threatening injuries present, go to step two.
- ♦ If other injuries present, but manageable in multi-place recompression chamber, consider transferring to multi-place chamber if available.

STEP TWO

Assess for DCS/AGE. This should be a rapid screening exam:

- ♦ Does the subject complain of any weakness, paralysis, visual disturbance, or cognitive defect?
- ♦ Can the subject answer simple questions, recognize a visual object, stand, walk, reach above his head with both arms, and grip?
- ♦ If gross deficit found, go to step three.
- ♦ If no gross deficit, observe expectantly, treat other injuries when feasible, and provide fluids and surface oxygen if available. Re-assess periodically, and in more detail, when recompression chamber space available.
- ♦ If recompression assets available to treat large numbers of rescuees, group rescuees depending on other needs.

STEP THREE

Rule out possible contraindications to recompression in the EEHS:

- ♦ Unconsciousness (unless skilled personnel available)
- ♦ Any airway compromise
- ♦ Chest trauma
- ♦ Pneumothorax (particular attention to this should be paid if patient has rapidly developing neurologic symptoms which could be AGE).
- ♦ Traumatic injury
- ♦ Shock
- ♦ Head injury
- ♦ If contraindications exist, defer recompression until problems addressed (i.e., chest tube placed for pneumothorax, shock stabilized, or airway secured by skilled personnel). Alternately, consider treatment in multi-place chamber if available.
- ♦ If no contraindications, go to step four.

STEP FOUR

- ♦ Assess the likelihood of recovery compared to other candidates for recompression therapy if resources limited. Avoid dedicating scarce resources for an indeterminate time period in cases unlikely to recover.
- ♦ Also consider co-existent conditions other than DCS/AGE which would benefit from hyperbaric oxygen therapy, such as carbon monoxide poisoning or burns. While these conditions will probably not be the primary concern for decisions regarding allocation of EEHS or other recompression assets, they may be a factor.

STEP FIVE

- ♦ Decide whether patient is better candidate for multi-place recompression chamber or EEHS.
- ♦ If treatment were likely to be similar to others in a large group, multi-place chamber treatment would probably be more efficient.

- ♦ If patient has unique needs, EEHS may be better.
- ♦ Special considerations requiring preparation: If patient needs extensive preparation (i.e., chest tube, wound care, etc), it may be more efficient to treat another patient in the EEHS while this patient is being readied, or to treat patient in multi-place chamber. Conversely, if a large group is ready for treatment in the multi-place chamber, a patient with special needs that might delay treatment of the remainder of the group could be treated in the EEHS.

STEP SIX

- ♦ If all of prior considerations lead to choice of EEHS for treatment, place patient in EEHS at earliest opportunity, using criteria discussed above to prioritize which patients will be treated first. Teach use of BIBS and equalization techniques, and compress. Give 100% oxygen via BIBS system. Assess for response to treatment.
- ♦ All patients should be evaluated continuously. If a patient not under recompression deteriorates to the point that his symptoms exceed those of patients currently in EEHS, consider decompressing the least serious patient from the EEHS in order to recompress more seriously injured patients, but weigh this decision very carefully.
- ♦ If evacuation is a possibility, consider transport under pressure using EEHS, but weigh risk and logistic difficulty of EEHS versus need for continuous recompression. Also consider that evacuation in the EEHS means loss of the EEHS for other patients awaiting recompression.

APPENDIX B3

TRIAGE ALGORITHM FOR EVACUATION

The decision to evacuate a patient under pressure using an EEHS requires careful consideration of multiple factors:

STEP ONE

- ♦ Are the injuries for which evacuation is being considered truly life or limb threatening?
- ♦ Will the treatment capabilities of the receiving facility really make a significant difference in the patient's ultimate outcome?
- ♦ If not, consider treatment on-site, with or without the EEHS or other recompression asset.

STEP TWO

- ♦ Does the patient have a compelling need for transport under pressure? Has he had a saturation exposure without adequate decompression? Does he have neurological involvement of DCS or AGE? (See Appendix B-1.) If not, consider transport with standard support, with surface oxygen supplementation if possible.
- ♦ What is the evacuation time/distance? For short transports, the lack of pressure during transport may be insignificant when weighed against the extra time and complexity of using the EEHS. For example, if recompression facilities are on shore or another vessel less than one hour away, it may make more sense to transport without the EEHS.
- ♦ Are the operational factors, such as weather, sea state, and vessel characteristics favorable for evacuation? Often, the hazards involved in evacuation may exceed the benefit.

STEP THREE

- ♦ Is the patient a suitable candidate for use of the EEHS? Are there contraindications or special needs? (See Appendix B1.)

STEP FOUR

- ♦ Are there sufficient recompression assets on scene to treat other patients? Will the loss of the EEHS used for evacuation, and the trained personnel required for its use, compromise the care of other patients?

STEP FIVE

- ♦ If all of the above factors have been considered and evacuation using the EEHS is elected, prepare the patient for entry into the EEHS and evacuation using transport under pressure procedures.

STEP SIX

- ♦ Specific treatment protocols are covered in Appendix C.

APPENDIX C

EEHS TREATMENT SCHEDULES

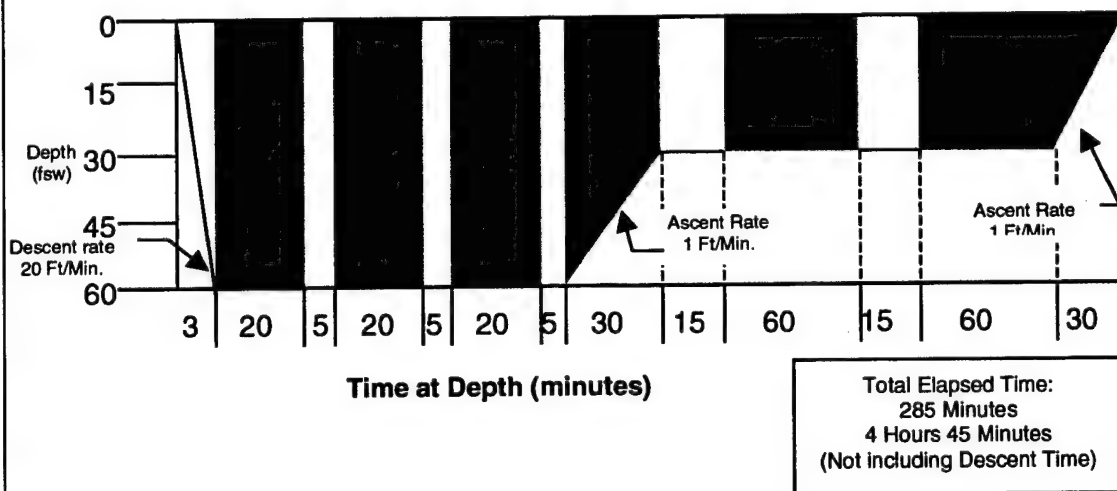
TREATMENT OF NON-SATURATION DCS

Patients with DCS not due to prior saturation should be treated using U.S. Navy Treatment Table 6 (TT6) under most circumstances. The following excerpt from the U.S. Navy Diving Manual provides the details¹.

Treatment Table 6

1. Descent rate – 20 ft/min.
2. Ascent rate – Not to exceed 1 ft/min. Do not compensate for slower ascent rates. Compensate for faster rates by halting the ascent.
3. Time on oxygen begins on arrival at 60 feet.
4. If oxygen breathing must be interrupted because of CNS Oxygen Toxicity, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption (see paragraph 21-5.5.6.1.1).
5. Table 6 can be lengthened up to 2 additional 25-minute periods at 60 feet (20 minutes on oxygen and 5 minutes on air), or up to 2 additional 75-minute periods at 30 feet (15 minutes on air and 60 minutes on oxygen), or both.
6. Tender breathes 100 percent O₂ during the last 30 min. at 30 fsw and during ascent to the surface for an unmodified table or where there has been only a single extension at 30 or 60 feet. If there has been more than one extension, the O₂ breathing at 30 feet is increased to 60 minutes. If the tender had a hyperbaric exposure within the past 12 hours an additional 60-minute O₂ period is taken at 30 feet.

Treatment Table 6 Depth/Time Profile



It should be noted that if TT6 is followed, particularly with respect to oxygen breathing cycles, the patient should not incur extra decompression obligation. If a situation develops where access to the patient is needed, he can be depressurized to surface pressure and removed from the EEHS for short periods, or his treatment can be terminated early. Interruption in treatment may reduce treatment effectiveness and

lead to incomplete resolution, worsening, or recurrence of symptoms, but would not be expected to be more dangerous than withholding treatment.

TREATMENT OF NON-SATURATION AGE

Treatment of AGE in a fully capable multi-place hyperbaric chamber would include, under some circumstances, compression to 165 fsw (50.3 msw) (6 ATA) (U.S. Navy TT6A). The SOS Hyperlite, as currently supplied, does not allow compression over 2.8 ATA, and for this reason treatment of AGE in the EEHS would follow TT6, with the considerations mentioned above.

Special precautions regarding pulmonary barotrauma should be taken in cases of suspected AGE. The patient should be carefully examined for signs of pneumothorax. If present, a chest tube with one-way valve (i.e., Heimlich valve) should be considered. If pneumothorax is suspected while under pressure in an EEHS, preparations for emergency placement of chest tubes upon decompression should be made, because decompression may produce a tension pneumothorax.

TREATMENT OF DCS AND AGE FOLLOWING A SATURATION EXPOSURE

If subjects have a history of saturation exposure, defined here as over four hours at a depth greater than 20 fsw (6.1 msw), and have had little or no decompression, TT6 may not provide adequate decompression time. Treatment may have to be lengthened. The following interim recommendations should be considered for treatment of DCS and AGE following a saturation exposure.

1. Compress to 60 fsw (18.3 msw) and begin treatment on Treatment Table 6. Recompression deeper than 60 fsw (18.3 msw) should not be undertaken.
2. Follow Treatment Table 6 to the completion of the 30 fsw (9.1 msw) stop using allowed extensions at 60 (18.3 msw) and 30 fsw (9.1 msw) to resolve symptoms, as needed.
3. Add the time spent on oxygen during the current treatment to any time spent on oxygen during prior treatments and during saturation decompression to calculate the patient's total oxygen time to that point.
4. Determine the oxygen time required for safe decompression from the DISSUB depth using the table below. Subtract the patient's total oxygen time from the required oxygen time to determine the patient's remaining omitted oxygen decompression time.

DISSUB Equivalent
Air Depth

Required Oxygen Time

20 fsw (6.1 msw)	0 minutes
30 fsw (9.1 msw)	130 minutes
40 fsw (12.2 msw)	240 minutes
50 fsw (15.2 msw)	480 minutes
60 fsw (18.3 msw)	600 minutes

5. If no omitted oxygen decompression time remains, complete Table 6 by surfacing from 30 fsw (9.1 msw) on oxygen at 1 fsw (.3 msw)/minute. If less than 170 minutes of omitted oxygen decompression time remains, ascend to 15 fsw (4.6 msw) at 1 fsw (.3 msw)/minute on oxygen, complete the remaining oxygen time at 15 fsw (4.6 msw), then ascend to the surface on oxygen at 1 fsw (.3 msw)/minute. If more than 170 minutes of omitted decompression time remain, complete any time in excess of 170 minutes at 30 fsw (9.1 msw), then ascend to 15 fsw (4.6 msw) at 1 fsw (.3 msw)/minute on oxygen, complete 170 minutes on oxygen at 15 fsw (4.6 msw), then ascend to the surface on oxygen at 1 fsw (.3 msw)/minute. Oxygen breathing during the additional time at 30 fsw (9.1 msw) and 15 fsw (4.6 msw) should be interrupted every 60 minutes with a 15 minute air break continuing the pattern of oxygen exposure begun at 30 fsw (9.1 msw) on Table 6.
6. If necessary, surface asymptomatic or nearly asymptomatic patients before completion of treatment to make room in the chamber for more emergent cases. Reduce the patient's omitted oxygen decompression time by the amount of oxygen time completed during the treatment. If omitted oxygen decompression time remains, additional oxygen recompression treatment should be administered when feasible under the triage scheme. In the interim, these patients should breathe surface oxygen and remain at rest in the supine position.
7. Once treatment is initiated, complete one Treatment Table 6 as a minimum even if the omitted oxygen decompression time is zero. Interrupt treatment only if premature surfacing is required to accommodate a more emergent case.
8. Allocate patients with recurrence of symptoms or new symptoms post treatment to recompression according to the triage rules. Once all the omitted oxygen decompression time has been completed, these patients may be managed as described in the U.S. Navy Diving Manual.

If saturation decompression has been completed prior to onset of DCS, TT6 has been shown to be effective and well tolerated after decompression from saturation

depths of up to approximately 50 fsw (15.2 msw). There is no experience at deeper saturation depths.

TREATMENT OF OMITTED DECOMPRESSION

Asymptomatic rescuees with omitted decompression are at significant risk for DCS. Whenever circumstances permit, these individuals should be recompressed and treated as outlined in the section immediately above. Treatment times may exceed 8-10 hours and thus treatment may be very difficult to tolerate in the confinement of the EEHS. Recompression could be started in the EEHS with the expectation of arrival of other recompression assets. As other assets become available, patients could be transferred under pressure to larger chambers. Patients should breathe oxygen and remain at rest in the supine position. Surface oxygen should be continued for a period not less than three times the omitted oxygen decompression time. All rescuees with omitted decompression should eventually receive recompression therapy.

TREATMENT OF OTHER CONDITIONS WITH HYPERBARIC OXYGEN

Several conditions likely to be encountered in a DISSUB situation could benefit from hyperbaric oxygen therapy, independent of whether DCS or AGE is present. Treatment should take into account any other recompression needs, but in general the following guidelines may be followed:

- Smoke Inhalation/Carbon monoxide poisoning - For mild to moderate cases, U.S. Navy Treatment Table 5 may be used. For severe cases, U.S. Navy Treatment Table 6 is recommended.
- Burns - 2.4 ATA (~45 fsw) (13.7 msw) for 90 minutes on 100% oxygen, as described in U.S. Navy Treatment Table 9².
- Crush injury or compartment syndrome - 2.4 ATA on 100% oxygen for 90 minutes (TT9).

USE OF EEHS FOR SATURATION DECOMPRESSION ON OXYGEN

BACKGROUND

In the absence of regular recompression facilities, saturation decompression on oxygen could be performed in the EEHS. A short surface interval would be required to transfer the rescuee from the water or rescue vehicle to the EEHS. The rescuee would then be recompressed back to the DISSUB depth and begin breathing oxygen. Short decompressions could be performed entirely in the EEHS. For long decompressions, the narrow confines of the EEHS are likely to become intolerable. Saturation decompression could be started in the EEHS with the expectation of arrival of other recompression assets. As other assets became available, rescuees could be transferred under pressure to the larger chambers.

The decompression procedures described in this section were designed for use in the DSRV³. They have been modified here for use in the EEHS. The procedures are the result of initial experiments performed at the Navy Experimental Diving Unit. They should be considered interim procedures. Final procedures will be issued when testing is complete.

DECOMPRESSION PROCEDURE

Table C1 gives the decompression times on oxygen needed to safely return pressurized rescuees to normal atmospheric pressure.

Table C1. Interim EEHS Oxygen Decompression Table

EAD (fsw)	Decompression Stop Depth (fsw)							Total O ₂ Time (min)
	45	40	35	30	25	20	15	
20	0	0	0	0	0	0	0	0
30	0	0	0	0	0	30	100	130
40	0	0	0	0	65	75	100	240
50	0	0	40	80	90	100	170	480
60	15	70	75	80	90	100	170	600

Basic Procedure. To use Table C1, follow these five steps:

1. First calculate the rescuee's Equivalent Air Depth (EAD), then enter Table C1 at the depth which is exactly equal or next greater than the calculated EAD. The EAD may be calculated from the following formula:

$$\text{EAD} = \frac{(D_{\text{sub}} + 33) (1 - FO_2)}{0.79} - 33$$

where: EAD = Equivalent Air Depth (fsw)

D_{sub} = DISSUB internal pressure or depth (fsw)

FO_2 = Fractional concentration of oxygen in DISSUB atmosphere

2. It will be necessary to have a surface interval to allow rescuees to transfer from the rescue vehicle to the EEHS. For equivalent air depths from 25 fsw (7.6 msw) to 60 fsw (18.3 msw), limit the surface interval to 15 minutes if possible.
3. As soon as the rescuee is in the EEHS, recompress the rescuee to the DISSUB depth (not to exceed 60 fsw) and initiate oxygen breathing using the built-in-breathing-system (BIBS). Breathe oxygen for at least one hour at the DISSUB depth (longer if possible), then decompress according to Table C1. Breathe

oxygen at each decompression stop for the time indicated in the table. Stop times are given in minutes.

4. The time spent breathing oxygen at the DISSUB depth prior to initiating decompression can be used as a credit to shorten the decompression time in Table C1. Subtract any time spent on oxygen prior to decompression from the decompression stop time, beginning with the shallowest stop first. For example, if the rescuee spent 60 minutes breathing oxygen at the DISSUB depth after recompression, subtract 60 minutes from the 15 fsw stop time.
5. Ascend to the first decompression stop and between decompression stops at 1-5 fsw/min (0.3-1.5 msw/min). Ascent time between stops is included in the subsequent stop time.
6. Upon completion of the last oxygen stop, switch the rescuee to air, and decompress to atmospheric pressure at 1-5 fsw/min (0.3-1.5 msw/min).

Air Breaks.

Periodic interruption of oxygen breathing in the EEHS is highly desirable to reduce the injurious effects of oxygen on the central nervous system and lung. Unexpected interruption of oxygen breathing may occur because of rescuee illness or injury.

When deeper than 45 fswg (actual depth, not EAD), interrupt oxygen breathing with at least five minutes of air breathing every 30 minutes. At 45 fswg and shallower, interrupt oxygen breathing with at least 10 minutes of air breathing every two hours. A pattern of 60 minutes on oxygen 15 minutes on air is considered optimal for minimizing lung injury and should be used 45 fswg and shallower whenever the added decompression time will not seriously compromise the rescue effort.

Once oxygen breathing is begun, consider any time spent on air to be "dead time" (i.e., not to count toward meeting the oxygen decompression requirement). Lengthen the total decompression time correspondingly so that all the required time on oxygen at each stop is completed.

Optimally, rescuees should be on oxygen for at least 15 minutes prior to decompression and should continue to breathe oxygen during decompression to the first stop. This, however, is not a requirement. Ascent to the first decompression stop may be made on air if necessary.

There is no contraindication to ascending between decompression stops while on air. Ascent time, however, should not be subtracted from the subsequent stop time if the rescuee is not on oxygen.

Credit for Oxygen Pre-Breathing.

Any time spent breathing oxygen in the DISSUB or in the rescue vehicle during transit can be used to reduce the decompression time once transfer to the EEHS has been effected. Reduce the oxygen time in Table C1 by one minute for each minute spent pre-breathing oxygen at the DISSUB depth. Subtract oxygen time from the decompression beginning with the shallowest decompression stop first. This subtraction is in addition to the subtraction for the time spent on oxygen at the DISSUB depth after recompression in the EEHS.

Time on air during pre-breathing in the DISSUB or in the rescue vehicle during transit should not exceed 15 minutes for each hour of oxygen breathed. Otherwise, some of the credit for oxygen pre-breathing described above will be lost. For each minute spent on air beyond 15 minutes per hour of oxygen, subtract two minutes from the oxygen pre-breathing time prior to subtracting the oxygen pre-breathing time from the oxygen decompression time in Table C1.

Example: A rescuer prebreathes oxygen in the DISSUB for two 60 minute periods separated by a 15 minute air break, then breathes air for 45 minutes in the rescue vehicle during transit from the DISSUB to the rescue platform. Thirty minutes on air is allowed for the two hours of oxygen breathed. The subject has spent a total of 60 minutes on air (15 minute air break + 45 minute transit). The excess air time is 30 minutes. Reduce the effective oxygen pre-breathing time from 120 to 60 minutes $[120 - (2 \times 30)]$. Subtract 60 minutes from the oxygen decompression time.

APPENDIX C REFERENCES

1. Naval Sea Systems Command, U.S. Navy *Diving Manual*, Vol. #5, Rev. 4, NAVSEA SS521-AG-PRO-010, Chapter 21, Page 41.
2. Ibid., Chapter 21, Page 46.
3. E. T. Flynn, G. W. Latson, J. Clarke, *Interim Procedures for Oxygen Decompression in the DSRV*, NEDU Technical Report, In Preparation, Navy Experimental Diving Unit.

APPENDIX D

TRANSPORT UNDER PRESSURE

Transport under pressure may involve one or more of several different steps. The patient may enter and exit the EEHS at surface pressure, or he may be transferred into or out of another recompression chamber while inside the EEHS. The latter involves equalizing the pressure of the larger chamber to the same pressure as the EEHS. Details are presented below:

TRANSPORT UNDER PRESSURE (NOT INVOLVING ENTRY OR EXIT IN ANOTHER CHAMBER)

- Patient enters EEHS, breathes oxygen from BIBS per selected treatment protocol. In general, the schedule for U.S. Navy Treatment Table 6 should be followed as closely as possible.
- The schedule for TT6 can be followed en route as long as adequate gas supplies are available.
- Control panel can be secured to top of EEHS.
- Gas supplies can be either secured to EEHS or carried alongside.
- Gas supplies may be disconnected for up to 15 minutes in order to load or unload EEHS into transport vehicle or carry over difficult terrain. Carbon dioxide levels will rise within the EEHS during this time. Ventilation of the chamber is recommended unless removal of the patient from the EEHS is imminent.
- Upon completion of treatment or arrival at receiving facility, depressurize EEHS per protocol and remove patient. If at altitude at the time of completion of treatment schedule, it would be advisable to keep patient in the EEHS at low pressure (e.g., 10 fsw (3 msw)) breathing air or oxygen as tolerated until return to ground level.
- Note that the EEHS can be depressurized for short periods to facilitate transport if necessary. While this is undesirable from a treatment standpoint, it should be viewed as something that can be done if necessary.

TRANSPORT IN AIRCRAFT

- Currently under review by United States Air Force¹. (This has been done in other countries, and approval is anticipated.)
- Consider that gauges may need to be adjusted or corrected for altitude, unless a self-contained depth gauge is placed within the EEHS.

- Securing of EEHS during flight is imperative in order to prevent the EEHS from rolling or having gas supply hoses dislodged.
- Communications may be difficult due to noise within the aircraft. Vigilance toward the patient is mandatory.
- Gas supply containers will need special approval/precautions.
- It is not advisable to depressurize EEHS while at altitude. If at altitude at the time of completion of treatment schedule, it would be advisable to keep the patient in the EEHS at low pressure (e.g., 10 fsw (3 msw)) breathing air or oxygen as tolerated until return to ground level.

TRANSFER OF PATIENT INTO MULTIPLACE RECOMPRESSION CHAMBER

- If multi-place chamber is at surface pressure, open hatches to inner and outer locks. Inspect for compatibility in terms of size, obstacles, etc. (If larger chamber cannot accommodate EEHS, make all necessary preparations, depressurize EEHS at a standard rate, remove patient and transfer into multi-place chamber as quickly as possible and repressurize as appropriate.)
- Prepare EEHS. Arrange control panel and gas supplies for easiest loading. Disconnect if necessary for up to 15 minutes.
- Transfer EEHS into multi-place chamber. EEHS can extend into both inner and outer lock if needed. One or more tenders must remain with the EEHS. Seal appropriate hatch.
- Secure gas supply to EEHS. Pressurize multi-place chamber to same pressure as EEHS. When pressures equalize, the end plates of the EEHS will lose their seal and can be removed. Remove patient from EEHS to the degree needed for care. If possible, fold the EEHS and place into outer lock for removal from chamber.

TRANSFER OF PATIENT OUT OF MULTIPLACE RECOMPRESSION CHAMBER

- If patient is in the inner lock and empty EEHS is outside, clear outer lock of all unnecessary articles. Remove the EEHS from package and arrange components in the outer lock in a manner that allows movement of hatches. If all components cannot be fitted well, two or more cycles of outer lock may be necessary.
- Pressurize the outer lock to mate with the inner lock. Transfer the EEHS into the inner chamber and assemble. It may be necessary for the EEHS to extend into both locks.

- Place the patient into the EEHS and place the end plates into position. Perform system checks. Pressurize the EEHS to a pressure slightly over the chamber pressure to create a seal.
- Slowly depressurize the chamber to surface. (Don't forget tender's possible decompression obligations.) Adjust EEHS pressure as appropriate, but maintain it above chamber pressure to keep seal.
- Remove the EEHS from the chamber and transport.

APPENDIX D REFERENCE

1. *Aeromedical Evacuation Test and Evaluation of the Emergency Hyperbaric Treatment/Evacuation System*, United States Air Force School of Aerospace Medicine, Davis Hyperbaric Medicine Division, Project Number 9974-XXX2, In progress.

APPENDIX E

CRITICAL CARE IN THE EEHS

There may be situations where severely injured patients will need to be treated in the EEHS. In general, the EEHS is not designed for such use, but with certain modifications and experienced medical personnel, many patients could be safely treated. Recommendations are divided into two levels of advanced care.

LEVEL I: MONITORING AND IV ACCESS

This would include patients with painful injuries requiring narcotic analgesia or sedation, antibiotics, vasopressors, anti-hypertensives, or other medications, but not unconscious, and with no airway compromise. Modification to the EEHS would be relatively simple, including a penetrator for intravenous line (and an infusion pump capable of overcoming EEHS pressure) and electrical connections for ECG monitoring. The manufacturer has indicated that this would be quite easy to provide. Further enhancements might include pulse oximetry and non-invasive blood pressure monitor, both of which have been used in monoplace treatment chambers.

A trained independent duty corpsmen or other paramedic could attend the patient with physician back up.

LEVEL II: INTENSIVE SUPPORTIVE CARE OR VENTILATORY ASSISTANCE

This would include unconscious patients, patients with airway compromise, or patients with cardiovascular instability. Modifications to the EEHS would include all of the above, plus options for providing ventilatory support for patients with an endotracheal tube in place. This adds a measure of complexity, but is not entirely impractical. Monoplace chambers in wide use (i.e., Sechrist) have a variety of ventilatory support systems that could be adapted to the EEHS.

A physician trained in both critical care and use of the EEHS with these accessories would be required. Many options exist for airway management in skilled hands, including oral or nasopharyngeal airways, and endotracheal intubation. Accessories for use of these devices, such as adapters for connection to the BIBS, should be available. With these accessories and the requisite training and experience, even very seriously injured patients could be effectively treated. For a review of equipment and procedures for critical care in the monoplace hyperbaric chamber, refer to the textbook, Hyperbaric Medicine Practice, by Eric Kindwall et al., Chapter 10¹.

We recommend at least 5-10 EEHS units, if not all, be equipped for Level I care. This would be relatively simple and inexpensive and cover the needs of many patients. Additionally, 3-5 EEHS units, or more, could be equipped for Level II care. Only specially trained physicians would use the advanced accessories as they arrive on scene.

APPENDIX E REFERENCE

1. E. Kindwall, *Hyperbaric Medicine Practice*, Best Publishing Co. Flagstaff, Arizona, 1995, Chapter 10.

APPENDIX F

NUMBER OF EEHS SYSTEMS REQUIRED

The approximate number of EEHS systems needed to support a submarine escape or rescue evolution can be estimated if three factors are known: (1) the rate at which men are delivered from the submarine to the platforms housing the EEHS systems, (2) the probability of decompression sickness (DCS) and arterial gas embolism (AGE) associated with the transfer, and (3) the average time required for treatment of DCS and AGE in the EEHS. The basic equation is:

$$N = (\text{Men/Load}) (\text{Loads/hr}) (\text{Rx Time}) [P_{\text{AGE}} + P_{\text{DCS}} (1 - P_{\text{AGE}})]$$

Where: N = number of EEHS systems required
Men/Load = number of men transferred during each cycle of the escape or rescue system
Loads/hr = number of loads arriving per hour
Rx Time = time required to treat DCS or AGE in the EEHS (hours)
 P_{AGE} = probability of arterial gas embolism (decimal %)
 P_{DCS} = probability of decompression sickness (decimal %)

The fourth term in the equation is the probability that an individual will suffer DCS and/or AGE. If the probability of AGE is zero, as it will be in most rescue scenarios because no ascent through the water column is required, the fourth term reduces simply to the probability of decompression sickness (P_{DCS}). If the probability of DCS is zero, as it would be in a shallow escape from an unpressurized submarine, the fourth term reduces simply to the probability of arterial gas embolism (P_{AGE}).

For EEHS planning purposes the following delivery rates can be assumed:

System	Delivery Rate
DSRV/MOSUB	24 men every 6 hours
SRC	6 men every 3 hours
Steinke Hood/Std Trunk	2 men every 20 minutes
SEIE System	2 men every 4 minutes

Table F1 shows the approximate probability of DCS as a function of the DISSUB internal pressure and the number of minutes of decompression taken on oxygen prior to surfacing. These numbers can be used along with the delivery rate information above to estimate required EEHS numbers in various escape and rescue scenarios.

Table F1. Probability of Decompression Sickness (%) vs. Decompression Time on Oxygen

EAD* (fsw)	Decompression Time on Oxygen (minutes)					
	0	120	240	360	480	600
20	0	-	-	-		
30	34	4	-	-		
40	65	35	5	-		
50	80	72	65	35	5	
60	87	80	72	65	35	5

*DISSUB internal pressure given as Equivalent Depth on Air (EAD). See Appendix C for the calculation of EAD.

The "zero" minute column in Table F1 shows the risk of direct ascent to the surface without decompression. This column applies both to escapes and to rescue with the SRC which does not have an onboard decompression capability. For escape, the additional risk of DCS associated with the pressurization in the escape trunk must be added to the risk in the zero column. For Steinke Hood escapes, an increase in P_{DCS} of 1.4% per 100 fsw of escape depth has been suggested by Parker et al.¹. For SEIE escapes, the increase is 0.6% per 100 fsw.

Example 1: Assume the DSRV delivers 24 submariners saturated at 50 fsw to the rescue MOSUB every six hours. Further assume that no more than 360 minutes of oxygen decompression can be provided in the DSRV prior to transfer of the rescuees in the MOSUB and that any DCS resulting from the transfer will require five hours to treat in the EEHS.

Solution: The number of men per load is 24, the number of loads per arriving per hour is 0.167 (one load every six hours), and the treatment time is five hours. From Table F1, the P_{DCS} associated with the transfer is estimated at 35% (0.35). The probability of AGE is zero. The number of chambers required is:

$$N = (24) (0.167) (5) (0.35) = 7$$

Example #2: Assume that men make a Steinke Hood escape from a pressurized submarine lying in 400 feet of water. The submarine's internal pressure is 30 fsw. Two men can escape every 20 minutes. Further assume that the P_{AGE} associated with the escape is 10% (0.1) and that the EEHS treatment time for DCS and/or AGE will be six hours.

Solution: The number of men delivered per load is two, the number of loads arriving per hour is three, and the treatment time is six hours. From Table F1, the P_{DCS} from the combined influence of the internal pressure of the boat plus the additional pressurization in the escape trunk to 400 fsw is estimated at $34.0 + 5.6 = 39.6\%$ (0.396). The probability of AGE is 0.1. The number of chambers required is:

$$N = (2) (3) (6) [0.1 + 0.396 (1 - 0.1)] = 16.4 \text{ or } 17$$

Treatment time in the EEHS will generally not be shorter than a standard Treatment Table 6 (285 minutes), but may be longer if extensions are required to achieve adequate resolution of symptoms. Extensions may also be required to compensate for omitted decompression (see Appendix C). The required oxygen decompression time for an internal DISSUB pressure of 30 fsw is 130 minutes; for 40 fsw, 240 minutes; for 50 fsw, 480 minutes; and for 60 fsw, 600 minutes. If some of this time is missed, it must be made up during treatment. For example, if DISSUB internal pressure is 60 fsw and no decompression is taken, not only would an 87% casualty rate be expected (see Table F1) but also treatments should be extended out to 600 minutes to compensate for the missed decompression. Both the high casualty rate and the lengthened treatment time increase the EEHS requirement.

APPENDIX F REFERENCE

1. Parker E. C., Ball R., Tibbles P. M., Weathersby P. K., *Escape from a Disabled Submarine: Decompression Sickness Risk Estimation*, Aviation, Space, and Environmental Medicine, 1999 Accepted for Publication.

APPENDIX G

REVIEW OF OTHER INFORMATION AVAILABLE

A search for other available information was conducted. Several technical reports and articles were reviewed. The most pertinent information is summarized below. The bibliography and references in this report contain additional information.

Qualification Testing on Four Emergency Evacuation Hyperbaric Stretchers (EEHS), Test Report #46769-01, Wyle Laboratories, Huntsville, Ala., 13 May 1998.

Technical report on the destructive and environmental testing of the chambers. This includes burst pressure testing on both units and results of exposure to heat, cold, ultraviolet radiation, and physical impact. The most notable result was hydrostatic testing to failure. The Hyperlite failed with non-catastrophic leakage at 215 psig, while the GSE Flexible Hyperbaric, despite being advertised as having greater strength, failed at a lower pressure, 200 psig, in a very dangerous, explosive loosening of the outer hatch. Subsequent to this result, the approved working pressure of the GSE Flexible Hyperbaric was lowered to 30.5 psig.

J. T. Florio, D. A. Elner, M. S. English, R. S. McKenzie, *Assessment of the Potential of a One Man Portable Recompression Chamber to Treat Submariners Suffering Decompression Illness Following Escape or Rescue*, Defence Research Agency, Alverstoke, England, DRA (AWL) Technical Memorandum 93711, June 1993.

A report on the possible uses of an EEHS system in the Royal Navy submarine rescue plans, and an overview of the Hyperlite system. It contains some useful historical information and calculations on gas supply requirements, as well as a review of testing done for the Lloyds Register for the Construction and Classification of Submersible and Diving Systems.

J. T. Florio, M. S. English, F. J. Stanley, *Evaluation of a One Man Compression Chamber for Submarine Rescue*, Defence Evaluation and Research Agency, DERA/SS/ES/CR971011/1.1, February 1998.

Specific testing completed by the Royal Navy Defence Evaluation and Research Agency (DERA) on the SOS Hyperlite EEHS. Includes results of manned and unmanned trials and useful calculations and data on the rise in carbon dioxide and fall of oxygen levels with the gas supplies disconnected. They found that the chamber was suitable for performing RN Table 62, which is very similar to U.S. Navy Treatment Table 6, and that transfer under pressure into another chamber was not problematic. They did note some deficiencies with the BIBS regulator performance, which have since been resolved. Durability testing included over 100 cycles of packing and unpacking with over ten cycles of pressurization, with acceptable levels of wear. Noise levels were found to be within acceptable limits.

SOS Limited, *Hyperlite Hyperbaric Stretcher; Model 585/3.1/3*, London, England, 24 December 1997.

Contains assembly and operating procedures, and details of parts including schematics, weights, and dimensions. In general, it is well written and easily understandable. It includes useful ancillary information such as a table for correcting pressure gauge readings for altitude. It also contains information on accessories and maintenance procedures.

Kindwall, *Hyperbaric Medicine Practice*, Best Publishing Co. Flagstaff, Arizona, 1995.

This textbook on hyperbaric medicine, particularly the chapter on use of monoplace hyperbaric chambers, is highly recommended for any medical personnel planning to use the EEHS. Nationwide, there are hundreds of monoplace chambers in use in hospitals, and the experience gained is well presented in this text. A new edition has been published in 1999, but is not available at the time of this report.